

# THE RELATIVISTIC PRECESSION MODEL FOR QPOS IN LOW MASS X-RAY BINARIES

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## ABSTRACT

The relativistic precession model for quasi periodic oscillations, QPOs, in low mass X-ray binaries is reviewed. The behaviour of three simultaneous types of QPOs is well matched in terms of the fundamental frequencies for geodesic motion in the strong field of the accreting compact object for reasonable star masses and spin frequencies. The model ascribes the higher frequency kHz QPOs, the lower frequency kHz QPOs and the horizontal branch oscillations to the Keplerian, periastron precession and nodal precession frequencies of matter inhomogeneities orbiting close to the inner edge of the accretion disk. The remarkable correlation between the centroid frequency of QPOs in both neutron star and black hole candidate low mass X-ray binaries is very well fit by the model. QPOs from low mass X-ray binaries might provide an unprecedented laboratory to test general relativity in the strong field regime.

KEYWORDS: accretion – black hole physics – relativity – stars: neutron – X-rays: stars

## 1. INTRODUCTION

Old accreting neutron stars, NSs, in low mass X-ray binaries, LMXRBs, display a complex variety of quasi-periodic oscillation, QPO, modes in their X-ray flux. The *low frequency* QPOs ( $\sim 1 - 100$  Hz) that were discovered and studied from high luminosity Z-sources in the eighties are further classified into horizontal, normal and flaring branch oscillations (HBOs, NBOs and FBOs, respectively), depending on the simultaneous position occupied by a source in the X-ray colour-colour diagram (for a review see van der Klis 1995). The kHz QPOs ( $\sim 0.2$  to  $\sim 1.3$  kHz) that were revealed and investigated with RXTE in a number of NS LMXRBs (see van der Klis 1998, 1999, 2000 and references therein) involve timescales similar to the dynamical timescales close to the NS. A common phenomenon is the presence of a pair of kHz QPOs (centroid frequencies of  $\nu_1$  and  $\nu_2$ ) which drift in frequency while maintaining their frequency difference  $\Delta\nu \equiv \nu_2 - \nu_1 \approx 250 - 360$  Hz roughly constant. Detailed studies showed that in four sources  $\Delta\nu$  decreases significantly (by up to  $\sim 100$  Hz) as  $\nu_2$  increases; these are Sco X-1 (van der Klis et al. 1997), 4U1608-52 (Mendez et al. 1998a,b), 4U1735-44 (Ford et al. 1998) and 4U1728-34 (Mendez & van der Klis 1999). Owing to poor statistics, a similar variation of  $\Delta\nu$  in other sources would

have remained undetected (Psaltis et al. 1998).

kHz QPOs show remarkably similar properties across NS LMXRBs of the Z and Atoll groups, the luminosity of which differs by a factor of  $\sim 10$  on average. During type I bursts from six Atoll sources, a nearly coherent signal at a frequency of  $\nu_{burst} \sim 290 - 580$  Hz has also been detected (for a review see Strohmayer 2000). In a few cases  $\nu_{burst}$  is consistent, to within the errors, with the frequency separation of the kHz QPO pair  $\Delta\nu$  or twice its value  $2\Delta\nu$ . Yet there are currently two sources (4U1636-53, Mendez et al. 1999, and 4U1728-34, Mendez & van der Klis 1999) for which  $\nu_{burst}$  is significantly different from  $\Delta\nu$  and its harmonics.

The presence of HBOs has been firmly established in both Atoll and Z-sources. Their frequency,  $\nu_{HBO}$  ( $\sim 15$  to  $\sim 60$  Hz) shows an approximately quadratic dependence ( $\sim \nu_2^2$ ) on the higher kHz QPO frequency that is observed simultaneously in a number of sources. The frequency changes of the kHz QPOs and HBOs are positively correlated with the instantaneous accretion rate. Some evidence has also been found for an equivalent of the NBOs and FBOs of Z-sources (Wijnands et al. 1999; Psaltis, Belloni & van der Klis 1999).

A remarkable correlation between the centroid frequencies of QPOs (or peaked noise components) from LMXRBs has been recently discovered (Psaltis, Belloni & van der Klis 1999). This correlation extends over nearly 3 decades in frequency and encompasses both NS and black hole candidate, BHC, systems. The frequencies of these QPOs, despite their quasi-periodic nature, provide the most accurately measured observables of LMXRBs. A primary goal of any QPO model is therefore to explain the frequency range and dependence of the different QPO types of these sources. The basic features of the relativistic precession model, RPM, are reviewed here (Stella & Vietri 1998a, 1999; Stella, Vietri & Morsink 1999). In the RPM the QPO signals arise from the fundamental frequencies of the motion of matter in the vicinity of the NS. The corresponding orbits are supposed to be slightly eccentric and tilted. As in other models, the higher frequency kHz QPOs at  $\nu_2$  are produced by the  $\phi$ -motion (*i.e.* the Keplerian motion) of inhomogeneities orbiting the inner disk boundary, while the lower frequency QPO signal at  $\nu_1$  originates from their periastron precession, which is primarily determined by strong-field effects. The HBOs are due to the nodal precession in the orbits of the same inhomogeneities, an effect which is dominated by frame-dragging around fast-rotating collapsed stars. The RPM can be applied to BHCs as well.

## 2. PERIASTRON PRECESSION AND KHZ QPOS

We consider here only infinitesimally eccentric and tilted orbits, under the assumption that the motion of matter in the innermost disk regions is dictated by the star's gravity alone. In the case of a circular geodesic in the equatorial plane ( $\theta = \pi/2$ ) of a Kerr black hole of mass  $M$  and specific angular momentum  $a$ , the coordinate frequency measured by a static observer at infinity is

$$\nu_\phi = \pm M^{1/2} r^{-3/2} [2\pi(1 \pm aM^{1/2} r^{-3/2})]^{-1} \quad (1)$$

(we use units such that  $G = c = 1$ ). The upper sign refers to prograde orbits. If we slightly perturb a circular orbit in the  $r$  and  $\theta$  directions, the coordinate frequencies of the small amplitude oscillations within the plane (the epicyclic frequency  $\nu_r$ ) and in the perpendicular direction (the vertical frequency  $\nu_\theta$ ) are given by (see Stella & Vietri 1999 and references therein)

$$\nu_r^2 = \nu_\phi^2(1 - 6Mr^{-1} \pm 8aM^{1/2}r^{-3/2} - 3a^2r^{-2}) \quad , \quad (2)$$

$$\nu_\theta^2 = \nu_\phi^2(1 \mp 4aM^{1/2}r^{-3/2} + 3a^2r^{-2}) \quad . \quad (3)$$

In the Schwarzschild limit ( $a = 0$ )  $\nu_\theta$  coincides with  $\nu_\phi$ , such that the nodal precession frequency  $\nu_{nod} \equiv \nu_\phi - \nu_\theta$  is identically zero.  $\nu_r$ , instead, is always lower than the other two frequencies, reaching a maximum for  $r = 8M$  and going to zero at  $r_{ms} = 6M$ . This qualitative behaviour of  $\nu_r$  is preserved in the Kerr field ( $a \neq 0$ ). Therefore the periastron precession frequency  $\nu_{per} \equiv \nu_\phi - \nu_r$  is dominated by a “Schwarzschild” term over a wide range of parameters (Stella & Vietri 1999).

In the RPM the higher and lower frequency kHz QPOs are identified with  $\nu_2 = \nu_\phi$  and  $\nu_1 = \nu_{per}$ , respectively. Therefore  $\Delta\nu \equiv \nu_2 - \nu_1 = \nu_\phi - (\nu_\phi - \nu_r) = \nu_r$ . For  $a = 0$ , Eqs. 1-2 give

$$\nu_r = \nu_\phi(1 - 6M/r)^{1/2} = \nu_\phi[1 - 6(2\pi\nu_\phi M)^{2/3}]^{1/2} \quad . \quad (4)$$

The curves in Fig. 1A show  $\nu_r$  vs.  $\nu_\phi$  for  $a = 0$  and selected values of  $M$ , the only free parameter in Eq. 4. The measured  $\Delta\nu$  vs.  $\nu_2$  for eleven NS LMXRBs is also plotted. It is apparent that for NS masses in the  $2 M_\odot$  range, the simple model outlined above is in qualitative agreement with the measured values, including the decrease of  $\Delta\nu$  for increasing  $\nu_2$  seen in Sco X-1, 4U1608-52, 4U1735-44 and 4U1728-34. The model above is only an approximation: first, the spacetime around a fast rotating NS is different from a Kerr spacetime (due to the star’s oblateness induced by rotation); second, the orbits might possess a finite (though small !) eccentricity. Analytical formulae to partly correct for these effects were derived by Stella & Vietri (1999); Fig. 1B shows the fit to the observed  $\Delta\nu$  vs.  $\nu_2$  relationship in Sco X-1 that was obtained through them. The orbital eccentricity, in particular, was varied in order to obtain different frequencies, while keeping the periastron distance  $r_p = a(1-e)$  fixed. The best model for a non-rotating NS is shown in Fig. 1B. The model reproduces fairly accurately the data with a minimum number of free parameters, the NS mass ( $M \sim 1.9 M_\odot$ ) and periastron distance ( $r_p \simeq 6.2 M$ ). The latter value is close to the marginally stable orbit radius. When the NS spin is allowed a finite value (say  $\nu_s \sim 300 - 600$  Hz), fits of very similar quality are obtained, the parameters of which differ only slightly from those given above. In essence, the effects induced by the NS rotation on  $\nu_r$  are small, though non-negligible.

The behaviour of the curves in Fig. 1A,B, and therefore the ability of the model to match the observations, reflects the properties of the strong field Schwarzschild metric, since lower order expansions fail to reproduce the observed frequencies (see Stella & Vietri 1999).

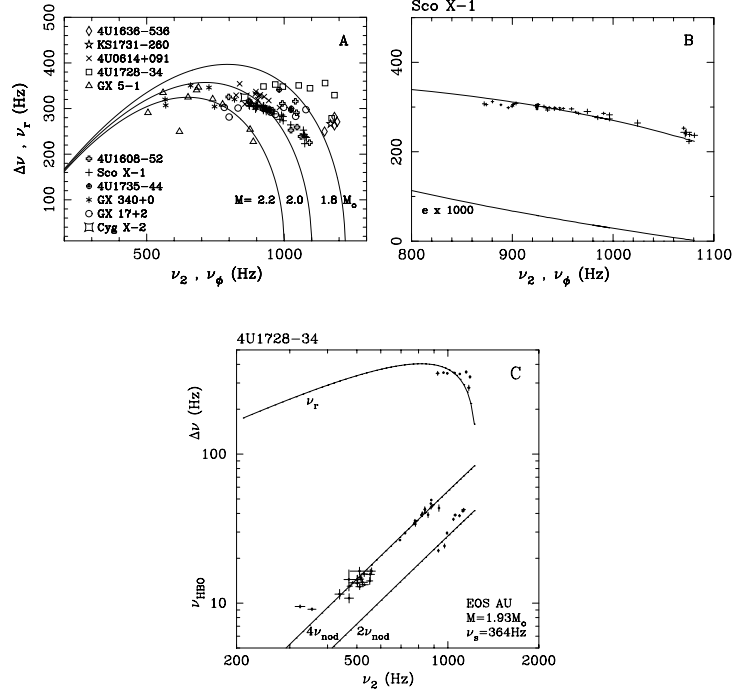


FIGURE 1. (A) kHz QPO frequency difference  $\Delta\nu$  versus higher QPO frequency  $\nu_2$  for eleven LMXRBs. Error bars are not plotted for the sake of clarity. The curves give the  $r$ - and  $\phi$ -frequencies of matter in nearly circular orbit around a non-rotating neutron star, of mass 2.2, 2.0 and  $1.8 M_\odot$ . (B)  $\Delta\nu$  versus  $\nu_2$  in Sco X-1. The best fit model corresponds to the  $r$ - and  $\phi$ -frequencies of matter orbiting a non-rotating  $1.90 M_\odot$  neutron star at a periastron distance of  $6.25 M$  (17.5 km). The line marked with  $e$  gives the orbital eccentricity ( $\times 1000$ ) as a function of the  $\phi$ -frequency. (C) kHz QPO frequency difference  $\Delta\nu$  and (double-branched) HBO frequency versus higher QPO frequency  $\nu_2$  in 4U1728-34 (Strohmayer et al. 1996; Ford & van der Klis 1998; Mendez & van der Klis 1999). The solid lines give the  $r$ -frequency and the 2nd and 4th harmonics of the nodal precession frequency  $\nu_{\text{nod}}$  as a function of the  $\phi$ -frequency for infinitesimally eccentric and tilted orbits in the spacetime of a  $1.93 M_\odot$  neutron star spinning at 364 Hz (EOS AU; Wiringa et al. 1988).

Within the RPM, the maximum value of  $\nu_r = \Delta\nu$  depends mainly on the mass of the compact object. The NS masses deduced from the simple modelling in Fig. 1A,B are in the  $\sim 1.8 - 2.0 M_\odot$  range, in agreement with the only relatively accurate mass measurement from optical spectro-photometry in any of these systems (Cyg X-2;  $M = 1.78 \pm 0.23 M_\odot$ ; Orosz & Kuulkers 1999). In general within the RPM,  $\Delta\nu$  should not be obviously related to the NS spin frequency  $\nu_s$ . Therefore, it seems natural to identify  $\nu_s$  with  $\nu_{burst}$ , *i.e.* the stable frequency seen during type I X-ray bursts (for a review see Strohmayer 2000). The distribution of NS spins inferred in this way is fairly wide ( $\sim 290 - 580$  Hz) and compares well with that of millisecond radio pulsars, MSPs, in agreement with evolutionary scenarios in which LMXRBs are the progenitors of MSPs. The 401 Hz spin of SAX J1808.4-3658, the only bursting LMXRB displaying coherent pulsations in its persistent emission (Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998), is also in the range of spin frequencies deduced from  $\nu_{burst}$ . None of the LMXRBs of the (high luminosity) Z-class has yet displayed burst oscillations; therefore their spin period is still to be measured. Cyg X-2 and GX 17+2, the only type I X-ray bursters in the group, might provide this important piece of information.

### 3. NODAL PRECESSION AND HBOS

If the orbits giving rise to the signals at  $\nu_\phi$  and  $\nu_{per}$  are slightly tilted relative to the equatorial plane, nodal precession will take place around the spin axis. In the RPM the HBO frequency is related to the nodal precession frequency. From Eqs. 1 and 3 this can be written in the slow rotation limit ( $a/M \ll 1$ )

$$\nu_{nod} \simeq 4\pi a \nu_\phi^2 \simeq 6.2 \times 10^{-5} (a/M) m \nu_\phi^2 \text{ Hz} \simeq 4.4 \times 10^{-8} I_{45} m^{-1} \nu_\phi^2 \nu_s \text{ Hz}, \quad (5)$$

where  $M = m M_\odot$ . This is the well known Lense-Thirring nodal precession formula. The latter equality refers to a rotating NS, where  $aM = 2\pi\nu_s I$  with  $I = 10^{45} I_{45} \text{ g cm}^2$  its moment of inertia.

If  $\nu_\phi$  and  $\nu_s$  are measured, the only parameter in Eq. 5 that is not identified from observations is  $I_{45} m^{-1}$ ; this can vary over a limited range,  $0.5 < I_{45} m^{-1} < 2$ , for virtually any mass and EOS (see the rotating NS models of Friedman, Ipser & Parker 1986 and Cook, Shapiro & Teukolsky 1992). The stellar oblateness induced by the star's rotation gives rise to correction terms in the nodal precession frequency also (see Morsink & Stella 1999 for a post-Newtonian formula). Their relative importance increases for high  $\nu_s$  and  $\nu_\phi$ . Yet the Lense-Thirring term dominates over a wide range of parameters, such that a  $\sim \nu_\phi^2$  dependence is expected for  $\nu_{nod}$ .

An approximately quadratic dependence of  $\nu_{HBO}$  on the higher frequency kHz QPOs has been measured in a number of LMXRBs. This dependence was originally suggested on the basis of a few power spectra of the Atoll source 4U1728-34 (Stella & Vietri 1998a). Ford & van der Klis (1998) analysed a large set of power spectra from the same source and determined that the frequency  $\nu_{low}$  of the  $\sim 10 - 50$  Hz QPOs scales as  $\nu_2^{2.11 \pm 0.06}$ . Note that the low frequency QPO vs.  $\nu_2$  relation of this source appears to be double-branched, with the centroid frequency shifting

by a factor of  $\sim 2$  across different observations. This suggests that on occasions the 2nd harmonic of  $\nu_{HBO}$  is excited instead of the fundamental. Stella & Vietri (1998b) first noticed that the HBO frequency of the Z-source GX 17+2 displays a nearly quadratic dependence on  $\nu_2$ . Psaltis et al. (1999) carried out a systematic study of Z-sources and determined that the HBO frequency is consistent with a  $\nu_2^2$  scaling (Cyg X-2 and Sco X-1 show evidence for a somewhat flatter dependence). In essence these results confirmed one of the basic features of the RPM, namely the nearly quadratic dependence of the nodal precession frequency on the  $\phi$ -frequency.

If the NS spin frequency is measured, then for any value of  $\nu_\phi$  the model yields a predicted nodal precession frequency which is uncertain only by a factor of a few, mainly due to the allowed range of  $I_{45}m^{-1}$  (Stella & Vietri 1998a). Only in the Atoll source 4U1728-34 burst oscillations and simultaneous kHz QPOs and HBOs have so far been detected unambiguously (Strohmayer et al. 1996; Ford & van der Klis 1998; Mendez & van der Klis 1999). Therefore its QPO frequencies can be used to test both the  $\nu_{HBO}$  and  $\Delta\nu$  versus  $\nu_2$  relationships predicted by the RPM, when the NS spin derived from burst oscillations is used ( $\nu_{burst} \simeq 364$  Hz). In order to take fully into account of all the effects that contribute determining geodetic motion in the vicinity of the NS, we adopted a numerical approach and computed the spacetime metric of the star using Stergioulas' (1995) code, an equivalent of that of Cook et al. (1992); see also Stergioulas and Friedman (1995). From this,  $\nu_r$  and  $\nu_{nod}$  were derived as a function of  $\nu_\phi$  for infinitesimally small tilt angles and eccentricities (Morsink & Stella 1999; Stella, Vietri & Morsink 1999).

Fig. 1C shows the measured values of  $\Delta\nu$  and  $\nu_{HBO}$  versus  $\nu_2$  in 4U1728-34. Relatively high NS masses (see also Sect. 2) and stiff EOSs such as AU and UU (Wiringa et al. 1988) are required in this application of the RPM. The solid lines in Fig. 1C are for a  $1.93 M_\odot$  NS with EOS AU and  $\nu_s = 364$  Hz. A good agreement is obtained if the HBO frequency, the lower of the two branches seen in 4U1728-34, is identified with the 2nd harmonics of  $\nu_{nod}$  (*i.e.*  $2\nu_{nod}$ ; see also Morsink & Stella 1999; Stella & Vietri 1999a). Correspondingly the upper HBO branch is well fit by  $4\nu_{nod}$ . The geometry of tilted orbits in the innermost disk regions might be such that a stronger signal is produced at the even harmonics of the nodal precession frequency (e.g. Psaltis et al. 1999). The frequency range and trend of the epicyclic frequency  $\nu_r$  in this model are also in reasonable agreement with the  $\Delta\nu$  measurements; a more complex model is clearly required in order to fit these data more accurately.

In summary, the model presented here is capable of reproducing the salient features of both the  $\Delta\nu$  versus  $\nu_2$  and  $\nu_{HBO}$  versus  $\nu_2$  relationships, with just two free parameters ( $M$  and the EOS), the allowed range of which is fairly limited (moreover the EOS cannot even be varied continuously !). Concerning Z-sources and all other Atoll sources for which burst oscillations have not been detected yet, the NS spin can still be regarded as a free parameter. The application of the RPM to the HBOs of these sources can therefore be used to constrain the spin of their NSs. Conversely, in those Atoll source in which  $\nu_{burst}$  is measured, but HBOs have not been detected yet, the RPM can be used to predict  $\nu_{HBO}$ . These issues are briefly addressed in the next Section.

#### 4. THE RELATIVISTIC PRECESSION MODEL AND THE PBV CORRELATION

Psaltis, Belloni & van der Klis (1999) recently identified two QPOs and peaked noise components the frequency of which follows a tight correlation over nearly three decades. This correlation (hereafter PBV correlation) involves both NS and BHC LMXRBs spanning different classes and a wide range of luminosities (see the points in Fig. 2). In kHz QPO NS systems, these components are the lower frequency kHz QPOs,  $\nu_1$ , and the low frequency, HBO or HBO-like QPOs,  $\nu_{HBO}$ . For BHC systems and lower luminosity NS LMXRBs the correlation involves either two QPOs, or a QPO and a peaked noise component. In all cases the frequency separation is about a decade and an approximate linear relationship ( $\nu_{HBO} \sim \nu_1^{0.95}$ ) holds. The QPO frequencies from the peculiar NS system Cir X-1 varies over nearly a decade while closely following the PBV correlation and bridging its low and high frequency ends. Psaltis, Belloni & van der Klis (1999) noted also that the  $\nu_2$  vs.  $\nu_1$  relations of different Atoll and Z-sources line-up with good accuracy.

The RPM matches precisely the PBV correlation, without resorting to any additional assumption (see Stella, Vietri & Morsink 1999). We assume that in all QPO sources, including BHCs,  $\nu_{HBO} \simeq 2\nu_{nod}$  as in 4U1728-34 (see Sect.3). Fig. 2A shows  $2\nu_{nod}$  and  $\nu_\phi$  obtained from Eqs. 1-3 as a function of  $\nu_{per}$  for corotating orbits and selected values of  $M$  and  $a/M$ . The high frequency end of each line is dictated by the orbital radius reaching the marginally stable orbit.

The separation of the lines in Fig. 2A testifies that while  $\nu_{nod}$  depends weakly on the mass and more strongly on  $a/M$ , the opposite is true for  $\nu_\phi$ . By taking the weak field ( $M/r \ll 1$ ) and slow rotation ( $a/M \ll 1$ ) limit of Eqs. 1-3 the relevant first order dependence is made explicit,

$$\nu_\phi \simeq (2\pi)^{-2/5} 3^{-3/5} M^{-2/5} \nu_{per}^{3/5} \simeq 33 m^{-2/5} \nu_{per}^{3/5} \text{ Hz} , \quad (6)$$

$$\nu_{nod} \simeq (2/3)^{6/5} \pi^{1/5} (a/M) M^{1/5} \nu_{per}^{6/5} \simeq 6.7 \times 10^{-2} (a/M) m^{1/5} \nu_{per}^{6/5} \text{ Hz} . \quad (7)$$

For the case of rotating NSs we adopt the numerical approach outlined in Sect. 3. Results are shown in Fig. 2B for a NS mass of  $1.95 M_\odot$ , EOS AU and  $\nu_s = 300, 600, 900$  and  $1200$  Hz (corresponding to  $a/M = 0.11, 0.22, 0.34$  and  $0.47$ , respectively). Note that the approximate scalings in Eqs. 6-7 remain valid over a wide range of frequencies. Only for the largest values of  $\nu_{per}$  and  $\nu_s$ ,  $\nu_{nod}$  departs substantially from the  $\sim \nu_{per}^{6/5}$  dependence.

The measured QPO and peaked noise frequencies giving rise to the PBV correlation are also plotted in Fig. 2B. Higher kHz QPO frequencies from NS systems ( $\nu_2$ ) are included (for the sake of clarity NBOs and FBOs were excluded). The agreement over the range of frequencies spanned by each kHz QPO NS system should not be surprising: together with the accurate matching of the corresponding  $\nu_1 - \nu_2$  relationship in Z-sources, this is indeed part of the evidence on which the RPM model was proposed. However the fact that the dependence of  $\nu_{nod}$  on  $\nu_{per}$  matches the observed  $\nu_{HBO} - \nu_1$  correlation to a good accuracy over  $\sim 3$  decades in frequency

(down to  $\nu_1$  of a few Hz), encompassing both NS and BHC systems, provides additional independent evidence in favor of the RPM. The observed variation of  $\nu_{HBO}$  and  $\nu_1$  in individual sources (Cir X-1 is the most striking example, see Fig. 2B) further supports the scaling predicted by the RPM. The matching of the observed  $\nu_2$  vs.  $\nu_1$  relation in terms of  $\nu_\phi$  vs.  $\nu_{per}$  is also quite accurate.

For EOS AU and  $m = 1.95$ , the  $\nu_{HBO}$  vs.  $\nu_1$  values of most NS LMXRBs are best matched for  $\nu_s$  in the  $\sim 600$  to  $900$  Hz range. It is apparent from Fig. 2B that  $\nu_s$  as low as  $\sim 300$  Hz are required for the Atoll sources with  $\nu_{HBO}$  somewhat below the main PBV correlation: these are 4U1728-34 (see Sect. 3) and 4U1608-52 (from which burst oscillations have not been detected yet). The values above are close to the range of  $\nu_s$  inferred from  $\nu_{burst}$  in a number of other Atoll sources (van der Klis 1999). Z-type LMXRBs appear to require  $\nu_s$  in the  $\sim 600$  to  $900$  Hz range, a possibility that is still open since for none of these sources there exists yet a  $\nu_s$  measurement. Note that the upper HBO branch of 4U1728-34 matches well the main PBV correlation. In the interpretation of Sect. 3 the lower branch corresponds to  $2\nu_{nod}$  and the upper branch to  $4\nu_{nod}$ . One could further speculate that sources following the main PBV correlation, Z-sources in particular, are also in the upper HBO branch at  $4\nu_{nod}$ ; in this case their  $\nu_s$  might be expected in the  $\sim 300 - 400$  Hz range.

For BHC LMXRBs the scatter around the PBV correlation implies values of  $a/M$  of  $\sim 0.1 - 0.3$  (see Fig. 2B). The points from XTE J1550-564, while inconsistent with any single value of  $a/M$ , might lie along two distinct branches separated by a factor of  $\sim 2$  in  $\nu_{HBO}$ , similar to the case of 4U1728-34. In the RPM the high frequency BHC QPOs (*e.g.* the  $\sim 300$  Hz QPOs of GRO1655-40) are interpreted in terms of  $\nu_1 = \nu_{per}$ . This is at variance with the  $\nu_1 = \nu_{nod}$  interpretation of Cui et al. (1998), which requires high values of  $a/M$  ( $\sim 0.95$  in GRO1655-40), in contrast with BHC accretion-driven spinup scenarios (King & Kolb 1999). From Fig. 2A it is apparent that the  $\sim 300$  Hz QPOs from GRO 1655-40 lie close to the high frequency end of the  $a/M = 0.1$ ,  $m = 7$  line. Since the mass of the BHC in GRO 1655-40 determined through optical observations is  $\sim 7 M_\odot$  (Shahbaz et al. 1999), we conclude that, according to the RPM,  $\nu_{per} \simeq 300$  Hz close to the marginally stable orbit, where by definition  $\nu_\phi = \nu_{per}$ . This suggests that any additional QPO signal at  $\nu_2 = \nu_\phi$  would be very close to or even blended with the QPO peak at  $\nu_1$ . The detection of two closeby or even partially overlapping QPO peaks close to  $\sim 300$  Hz in GRO 1655-40 would therefore provide further evidence in favor of the RPM interpretation.

## 5. DISCUSSION

### 5.1. Beat Frequency Models

In the alternative scenario provided by beat frequency models, BFMs, disk inhomogeneities at the magnetospheric boundary ( $r_m$ ) and the sonic point radius ( $r_s$ ) are accreted at the beat frequency between the local Keplerian frequency,  $\nu_\phi$ , and the NS spin frequency,  $\nu_s$ , giving rise to the HBOs ( $\nu_{HBO} = \nu_\phi(r_m) - \nu_s$ ) and the lower frequency kHz QPOs ( $\nu_1 = \nu_\phi(r_s) - \nu_s$ ), respectively (Alpar & Shaham 1985; Lamb



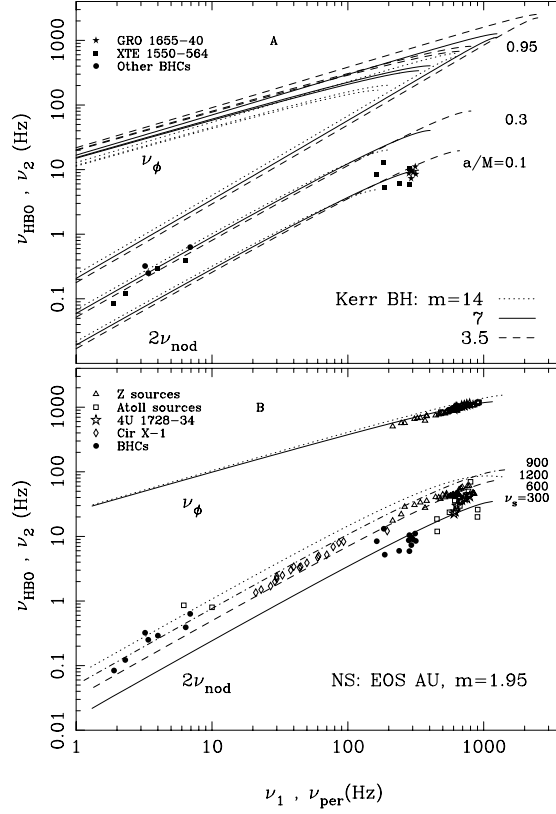


FIGURE 2. Twice the nodal precession frequency,  $2\nu_{\text{nod}}$ , and  $\phi$ -frequency,  $\nu_{\phi}$ , vs. periastron precession frequency,  $\nu_{\text{per}}$ , for black hole candidates of various masses and angular momenta (panel A) and rotating neutron star models (EOS AU,  $m = 1.95$ ) with selected spin frequencies (panel B). The measured QPO (or peaked noise) frequencies  $\nu_1$ ,  $\nu_2$  and  $\nu_{\text{HBO}}$  giving rise to the PBV correlation are also shown in panel B for both BHC and NS LMXRBs and in panel A for BHC LMXRBs only; errors bars are not plotted (see Psaltis, Belloni & van der Klis 1999 for a complete list of references). We included only those cases in which QPOs at  $\nu_1$  were unambiguously detected. NBO and FBO frequencies are not plotted.

et al. 1985; Miller et al. 1998). The higher frequency kHz QPOs are attributed to the Keplerian motion at the sonic point radius ( $\nu_2 = \nu_\phi(r_s)$ ). The frequency separation  $\Delta\nu$  therefore, yields the NS spin frequency,  $\nu_s$ . The narrow distribution of  $\nu_s$  inferred in this way ( $\sim 250 - 360$  Hz) is far from the mass shedding limit of any NS model and considerably less extended than that of fast MSPs ( $\sim 600$  Hz). Accordingly the NSs of LMXRBs should be equilibrium rotators with a narrow frequency range despite their different average mass transfer rates, magnetic field strengths and evolutionary histories. Moreover, if LMXRBs are the progenitors of MSPs, then BFMs would require a different evolutionary path leading to the formation of radio pulsars with  $\nu_s > 400$  Hz.

The fact that in some Atoll LMXRBs  $\nu_{burst} \simeq \Delta\nu$  (or  $\simeq 2\Delta\nu$ ) is readily interpreted, because in BFMs  $\nu_s \equiv \Delta\nu$ . Yet,  $\Delta\nu$  does vary and is significantly different from  $\nu_{burst}$  in several sources (see Sect. 1). This in contrast with the expectations of simple BFMs.

Attempts at fitting the PBV correlation within BFMs by using the range of spin frequencies inferred from  $\Delta\nu$  fail to produce a power-law like behaviour over a sufficiently large range of frequencies (see van der Klis 1999). This is because both  $\nu_1$  and  $\nu_{HBO}$  result from the difference of a variable frequency ( $\nu_\phi$  at  $r_s$  and  $r_m$ , respectively) and a fixed frequency ( $\nu_s$ ). Moreover, BFMs are not applicable to BHCs, since the *no hair theorem* excludes the possibility that an offset magnetic field or radiation beam can be stably anchored to the black hole, as required to produce the beating with the disk Keplerian frequency.

## 5.2. The Relativistic Precession Model

The RPM naturally explains the frequency range and dependence of the kHz QPOs and HBOs in NS LMXRBs, as well as the PBV correlation, which involves both NS and BHC systems. The model has a minimum number of free parameters. Predictions that can be tested through future analyses and/or observations include:

(a) The frequency difference  $\Delta\nu = \nu_r$  is expected to decrease also for low values of  $\nu_2 = \nu_\phi$  (see Eq. 4 and Fig. 1). Moreover if the highest  $\nu_2 = \nu_\phi$  frequencies do originate from nearly circular orbits (see Fig. 1A), then  $\Delta\nu$  should quickly decrease as  $\nu_2$  increases further and the orbital radius approaches the marginally stable orbit.

(b)  $\nu_2 = \nu_\phi$  is expected to scale as  $\nu_1^{3/5} = \nu_{per}^{3/5}$ . Extending the  $\nu_2$  vs.  $\nu_1$  correlation in NS systems toward lower frequencies and detecting the signal at  $\nu_2$  in BHC systems would provide important new tests.

In the RPM the QPO signals are produced at  $r/M \sim 100 m^{-2/5} \nu_{per}^{-2/5}$ , which, for individual sources, must decrease for increasing mass accretion rates (as  $\dot{M}$  is positively correlated with *e.g.*  $\nu_2$ ). The inferred radii range from close to the marginally stable ( $r/M \sim 6$ ) to  $r/M \sim 30$  over the frequency span covered by the PBV correlation. Many NS and BHC LMXRBs display two component X-ray spectra consisting of a soft thermal component, usually interpreted in terms of emission from an optically thick accretion disk, and a harder, often power-law like component, likely due to a hot inner disk region. The QPOs might originate at

the transition radius between the optically thick disk and the hot inner region as a result of occultation or modulated emission by inhomogeneities (Stella, Vietri & Morsink 1999; see also Di Matteo & Psaltis 1999).

Mechanisms that can induce a finite (though small) eccentricity and tilt in the motion of matter in the innermost disk regions are currently under investigation. In the case of NSs, some kind of resonance between the star spin and the motion of matter inhomogeneities (see *e.g.* Vietri & Stella 1998) might be responsible for the close commensurability of  $\nu_{burst}$  and  $\Delta\nu$  (or  $2\Delta\nu$ ) observed in a few sources. These issues will be addressed elsewhere.

A simple test-particle approximation has been adopted so far within the RPM. Much needed hydrodynamical calculations are still in their infancy; among other things these are hampered by uncertainties concerning the physics of the innermost disk regions. Yet we note that in the hydrodynamical approach explored by Psaltis & Norman (2000), the test particle frequencies (the same as in the RPM plus an additional frequency at  $\nu_\phi + \nu_r$ ) are selected by the response of an annulus in the disk, when this is subject to a wide-band input noise.

If confirmed, the RPM will provide an unprecedented opportunity to measure GR effects in the strong field regime, such as the periastron precession in the vicinity of the marginally stable orbit and the radial dependence of the Lense-Thirring nodal precession frequency. In principle, accurately measured kHz QPO and HBO frequencies would yield crucial information on the compact object such as its mass and angular momentum (*e.g.* by solving Eqs. 1-3 for  $m$ ,  $a/M$  and  $r$ ). Should suitable, additional observables be found, it might become possible to obtain a self-consistency check of the RPM, together with tests of GR in the strong field regime.

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